

Jet Propulsion Laboratory
California Institute of Technology

Overview of the ASPIRE Project's Supersonic Flight Tests of a Strengthened DGB

IEEE Aerospace Conference

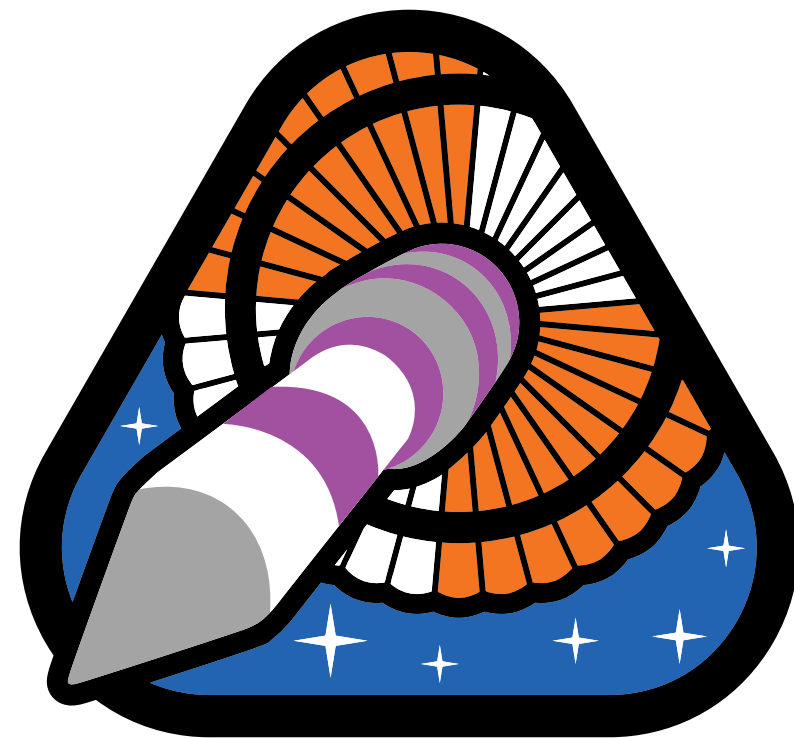
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March 4, 2019

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ASPIRE

The ASPIRE Project



- Disk-Gap-Band (DGB) parachute: developed in the 60s & 70s for Viking & successfully used in 7 8 (Congratulations InSight!) Mars missions.
- Recent experience suggests strength margins may have eroded¹
- **Advanced Supersonic Parachute Inflation Research Experiments Project**
Objectives:
 - Develop testing capability for supersonic parachutes at Mars-relevant conditions.
 - Deliver 21.5m parachutes to low-density, supersonic conditions on a sounding rocket test platform
 - Acquire data sufficient to characterize flight environment, loads, and performance
- Initial flights focused on testing candidate designs for Mars2020:
 - Built-to-print Mars Science Laboratory (MSL) Disk-Gap-Band (DGB)
 - Strengthened version of MSL DGB (identical geometry, stronger materials)

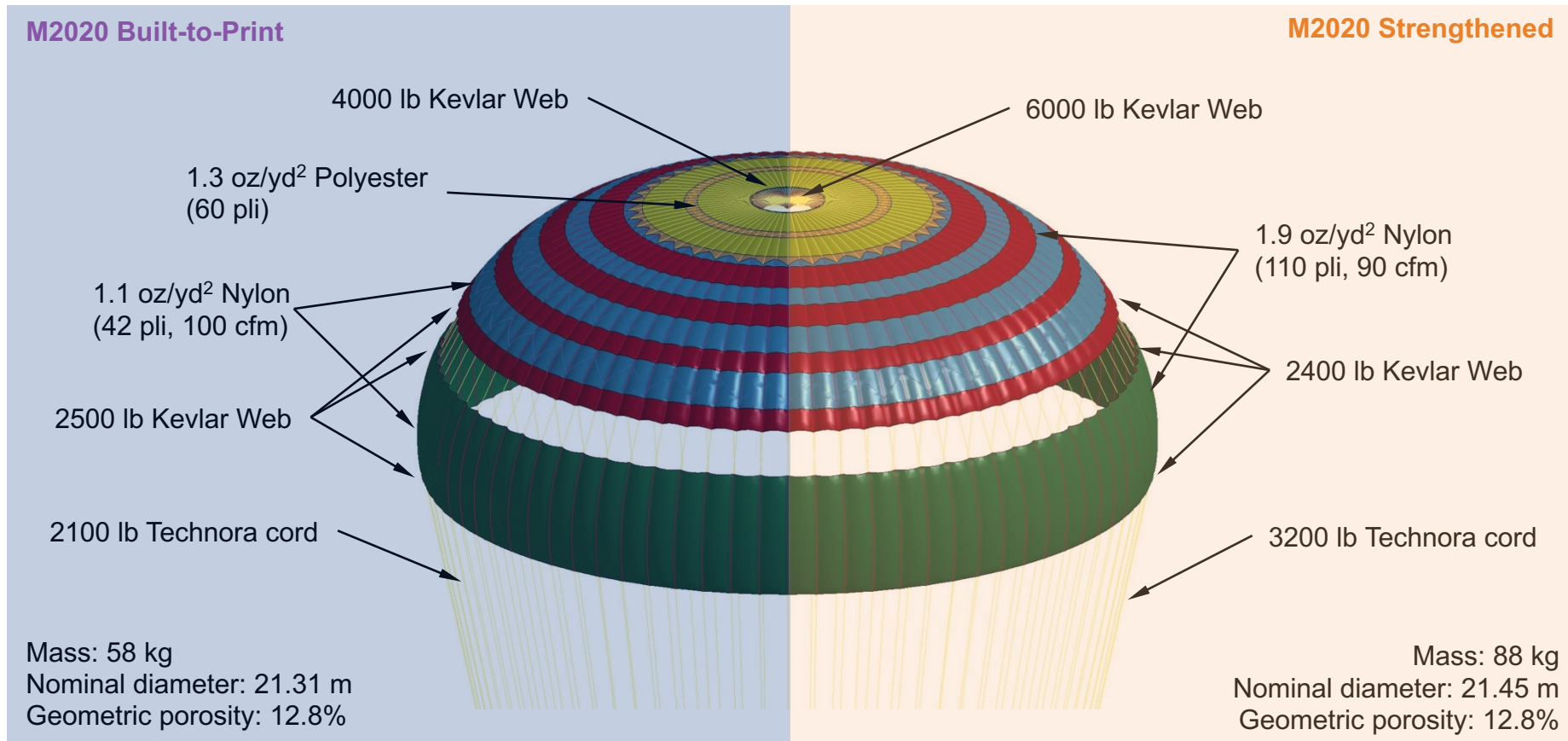
	Parachute	Target Load	Purpose	Test Date
SR01	MSL built-to-print	35 klbf (MSL @ Mars)	Test architecture shakeout. Ensure test approach doesn't introduce new parameters.	Oct. 4 th , 2017
SR02	Strengthened	47 klbf	Incremental strength test of new design.	Mar. 31 th , 2018
SR03	Strengthened	70 klbf	Strength test of new design	Sep. 7 th , 2018

¹Clark & Tanner, *IEEE Aerospace* 2017

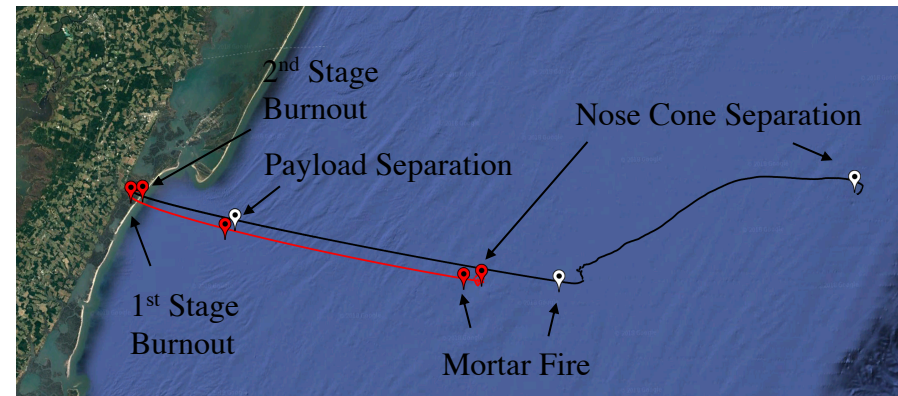
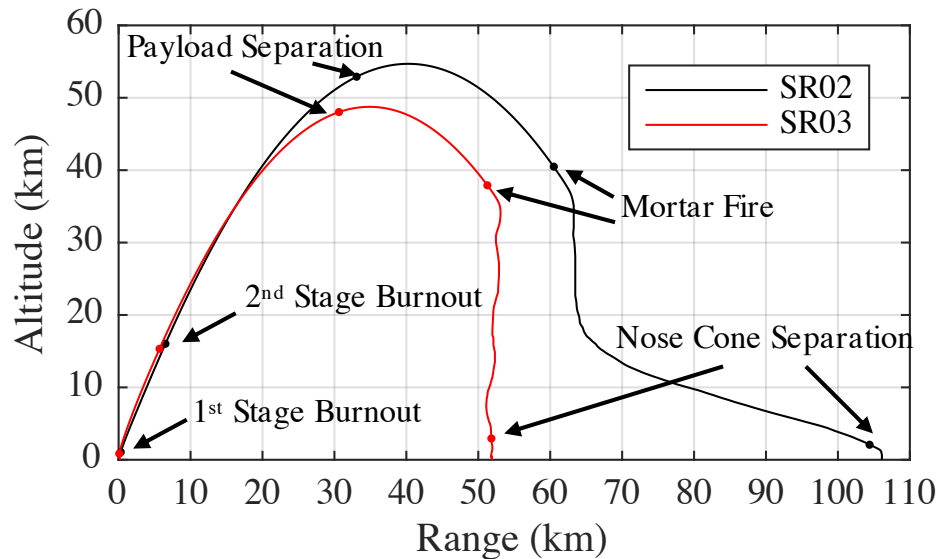


Two candidate designs for Mars2020:

- A build-to-print 21.5-m *MSL* DGB (tested to 35 klbf on SR01)
- Strengthened version of *MSL* DGB (identical geometry, stronger materials)



Test Conditions



SR02

Target mortar fire conditions: Mach = 1.72 q = 618 Pa
Target peak load q = 678 Pa

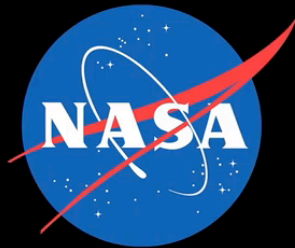
Event	Time from launch (sec)	Mach	Dynamic pressure (Pa)	Geodetic altitude (km)
Apogee	123.48	1.10	33	54.8
Mortar Fire	177.59	1.97	667	40.8
Line Stretch	178.63	2.00	746	40.3
Peak Load	162.08	1.97	748	40.0
Mach 1.4	180.72	1.4	417	39.3
Mach 1.0	182.86	1	234	38.6

SR03

Target mortar fire conditions: Mach = 1.76 q = 901 Pa
Target peak load q = 953 Pa

Event	Time from launch (sec)	Mach	Dynamic pressure (Pa)	Geodetic altitude (km)
Apogee	116.53	1.11	79	48.8
Mortar Fire	163.82	1.85	932	38.1
Line Stretch	164.85	1.88	1028	37.6
Peak Load	165.26	1.85	1020	37.5
Mach 1.4	166.15	1.4	615	37.1
Mach 1.0	167.59	1	334	36.9

SR02 Deployment & Inflation



Advanced Supersonic Parachute Inflation Research and Experiments (ASPIRE)

Flight # 002

Date: 31 March 2018

Location: Wallops Flight Facility, Wallops Island, VA

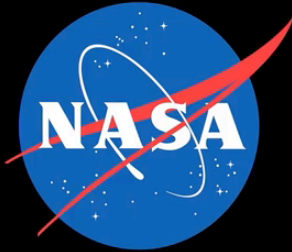
Payload: 21.51 m D₀ Disk-Gap-Band Supersonic Parachute



GENERAL DYNAMICS
Ordnance and Tactical Systems

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SR03 Deployment & Inflation



Advanced Supersonic Parachute Inflation Research and Experiments (ASPIRE)
Flight # 003
Date: 07 September 2018
Location: Wallops Flight Facility, Wallops Island, VA
Payload: 21.55 m D₀ Disk-Gap-Band Supersonic Parachute



GENERAL DYNAMICS
Ordnance and Tactical Systems

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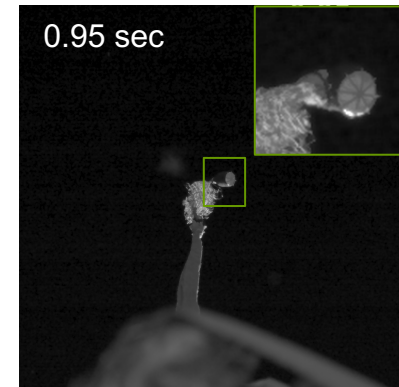
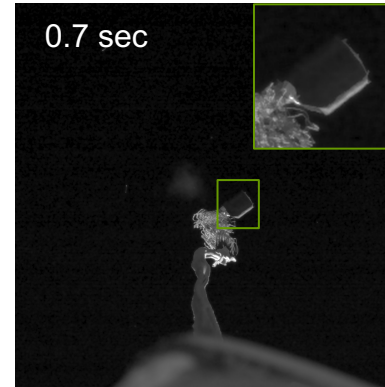
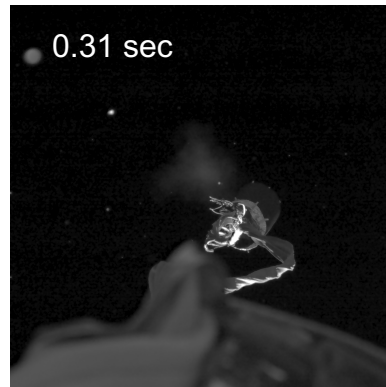
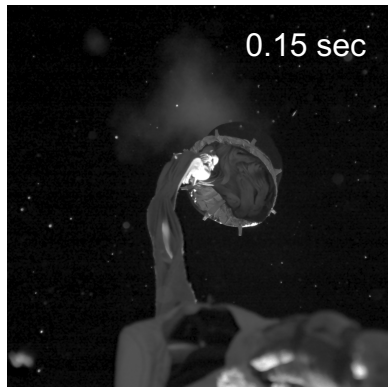
Parachute Deployment



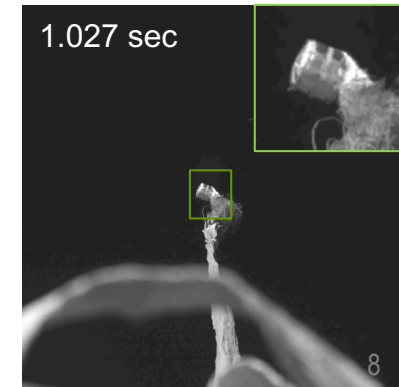
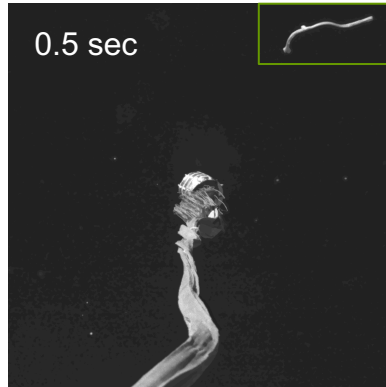
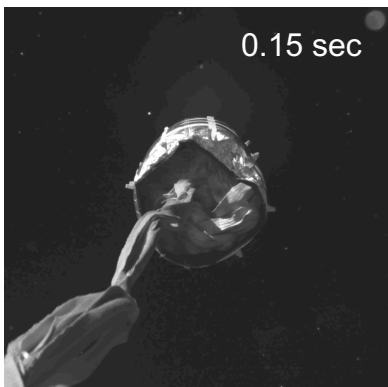
- Orderly deployment, no line entanglement
- Rotation of parachute pack $\sim 135^\circ$ on SR02, $\sim 90^\circ$ on SR03
- No major line sail
- SR03 FOD: ties, mortar o-ring

	SR02	SR03
Mortar exit velocity (flight)	46.7 m/s	47.3 m/s
Effective ground velocity (flight)	43.2 m/s	43.8 m/s
Mortar velocity (predicted)	44 m/s	44 m/s
Time to line-stretch (flight)	1.04 sec	1.03 sec
Time to line-stretch (predicted)	0.98 sec	0.99 sec

SR02

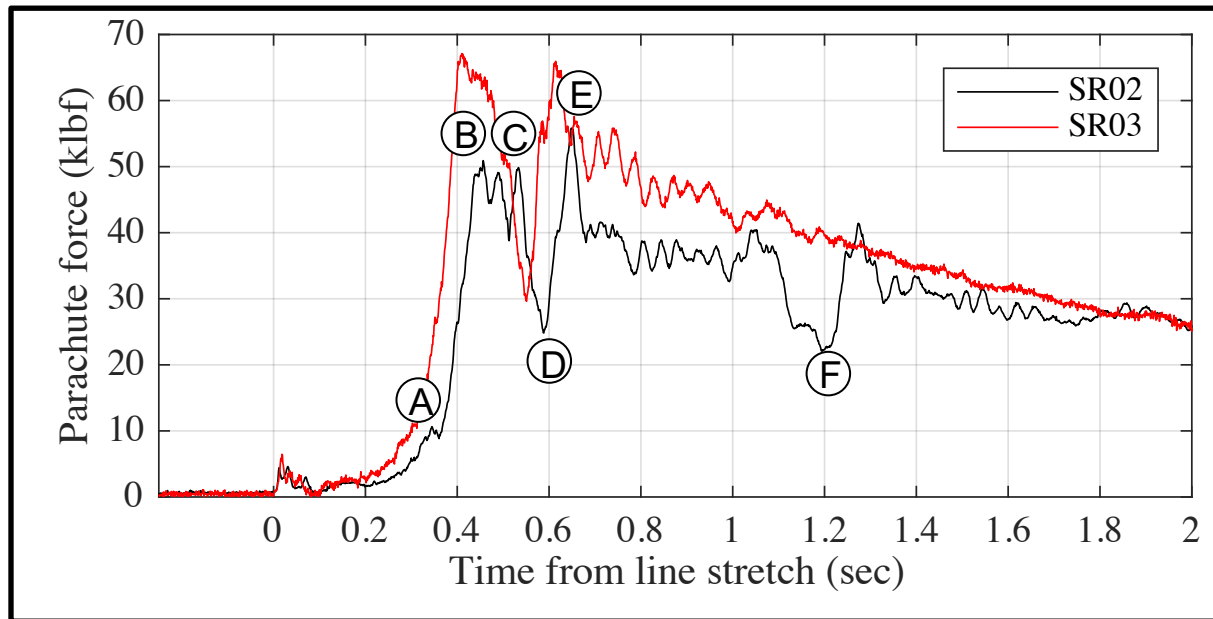
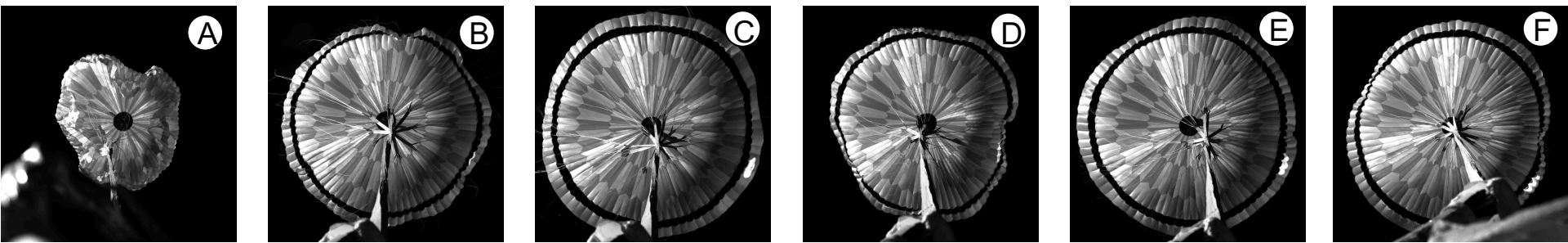


SR03



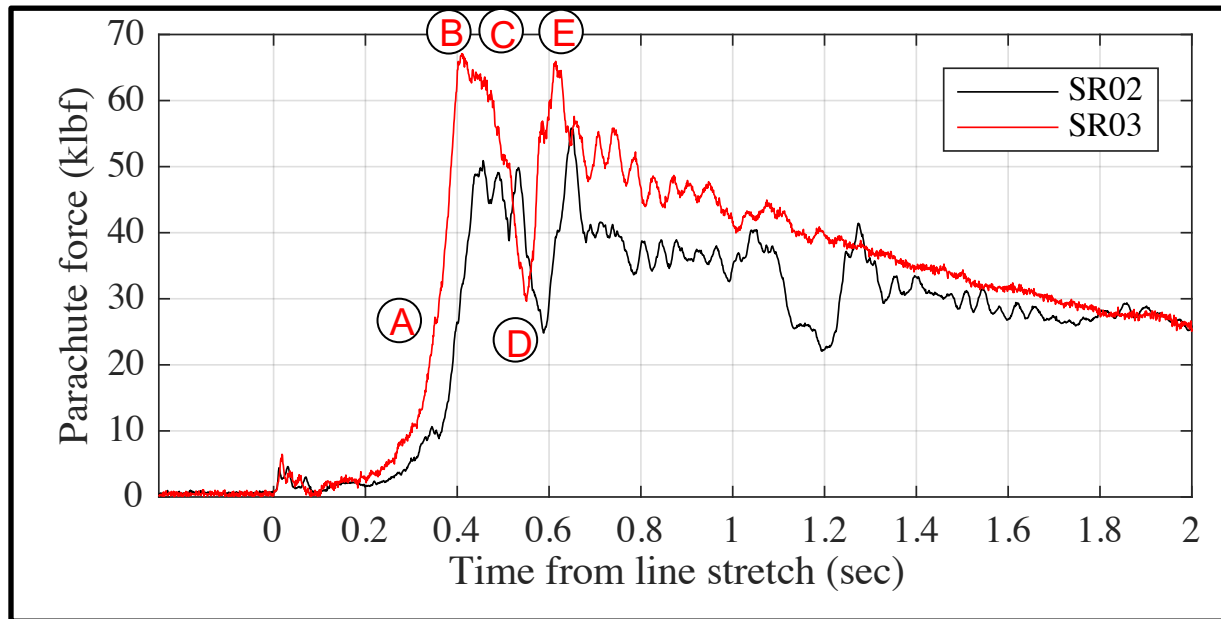
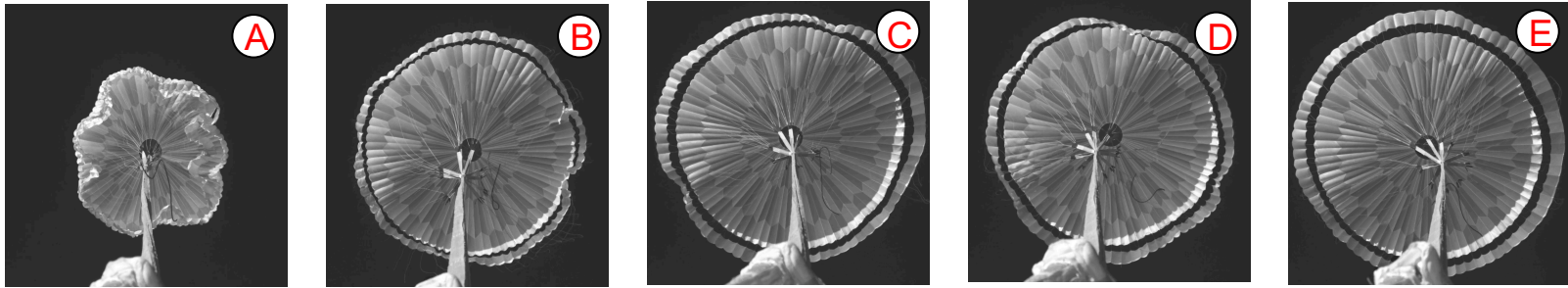
Times are from mortar fire

SR02 Parachute Inflation



- Portion of the band leads inflation, then stalls & inflation proceeds fairly symmetrically
- First peak force achieved ~20 ms before max. area
- After full area, moderate collapse & 50% decrease in load
- Second peak in force 10% larger than full inflation force
- Final load dip ~1.1 sec after line stretch

SR03 Parachute Inflation



- Faster, more symmetric inflation than SR02
- First peak force achieved ~20 ms before max. area
- After full area, moderate collapse & 50% decrease in load
- Second peak in force almost equal to full inflation force

Parachute Inflation



- Inflation predicted by *inflation distance* model¹: $\frac{L_{inf}}{D_0} = \alpha \left(\frac{\rho_c}{\rho_\infty} \right)$

	MSL	SR01	SR02	SR03
Inflation time (sec)	0.635	0.506	0.456	0.410
α	4.6	4.77	4.29	3.75

- Considering the conservation of momentum inside a control volume around the inflating canopy²:

$$F_{peak} = k_p (2q_\infty S_p)$$

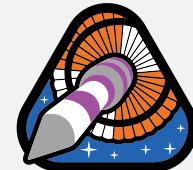
k_p = fraction of the fluid momentum converted to parachute drag

	MSL	SR01		SR02		SR03	
		1 st peak	2 nd peak	1 st peak	2 nd peak	1 st peak	2 nd peak
Load (klbf)	35	32.4	32.3	50.9	55.8	67.4	66.5
k_p	0.83	0.77	0.79	0.78	0.93	0.76	0.84

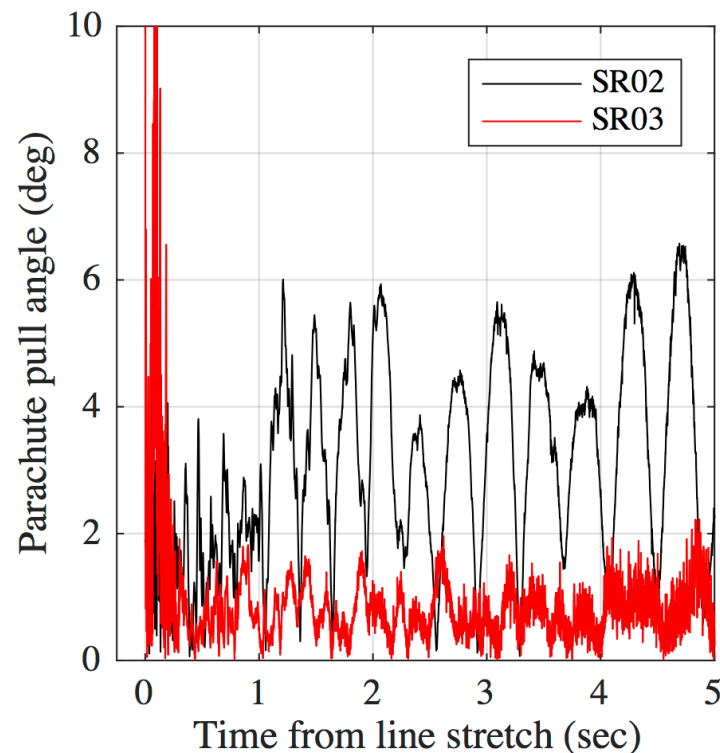
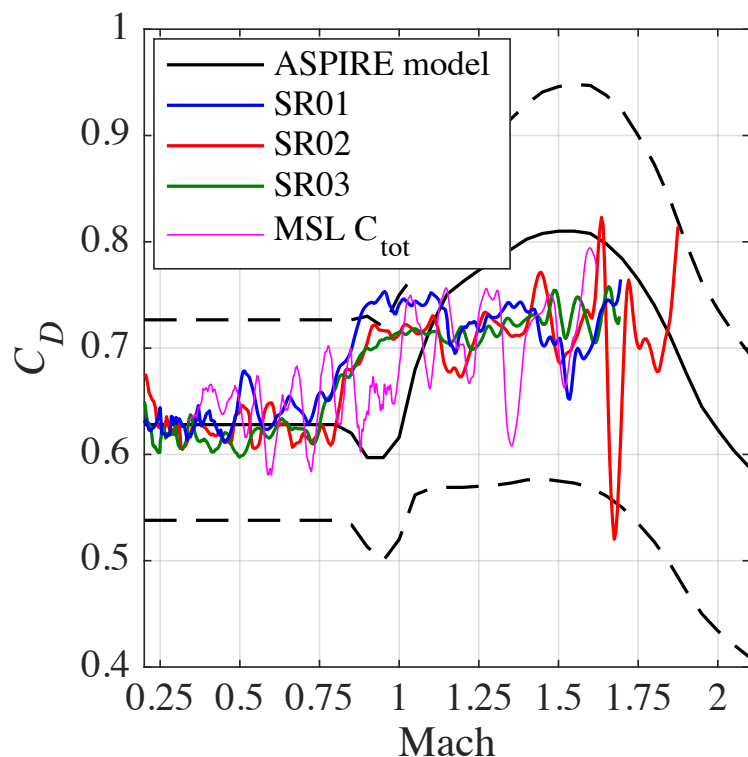
¹Greene, G. C., "Opening Distance of a Parachute," Journal of Spacecraft and Rockets 1, 1970.

²Way, D. *IEEE Aerospace Conference Paper #2817*, 2018

Parachute Aerodynamics



ASPIRE

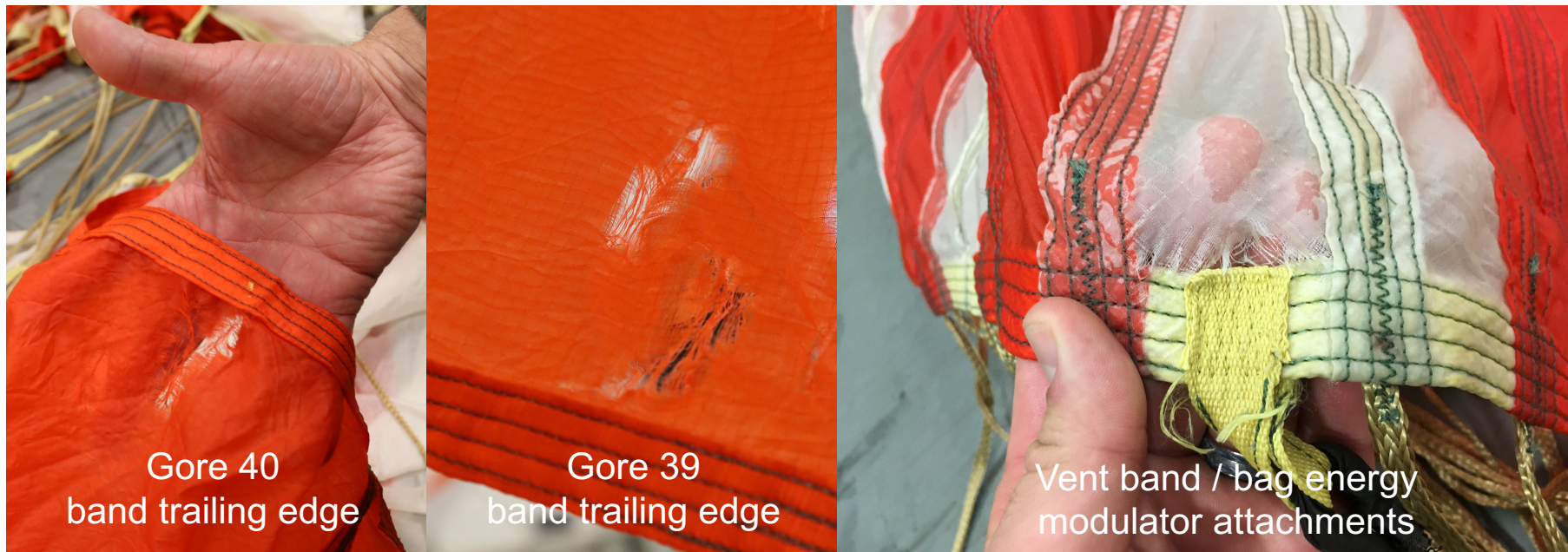


- C_D vs Mach: good agreement between SR01-3 & with MSL
- Good agreement with C_D model below $M = 0.75$, but over-estimated C_D for $M > 1.15$
- C_D remained constant in transonic region
- Parachute force vector “pull angle” larger on SR02, but remained below 10 deg
- Wind-relative total angle of attack oscillated about 15 deg for the majority of the flight

SR02 Post-Flight Inspection



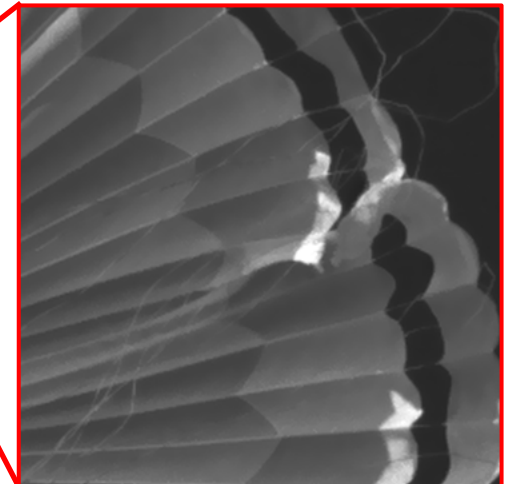
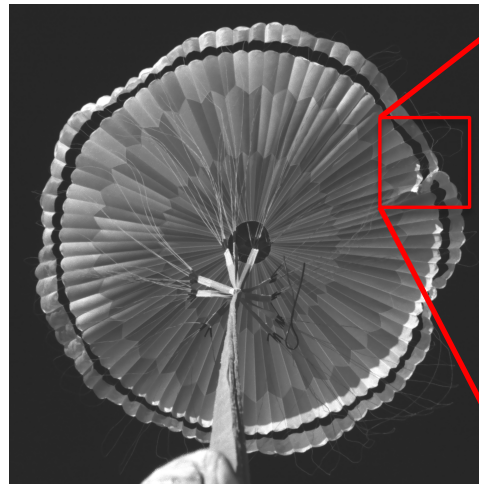
- Damage to parachute was minimal
- Appears to be mostly deployment related & caused by interaction with the bag or friction between adjacent surfaces
- Some minor damage to vent band at deployment bag attachment



Changes & SR03 Inspection



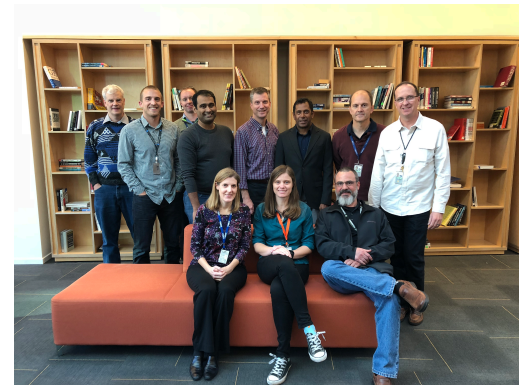
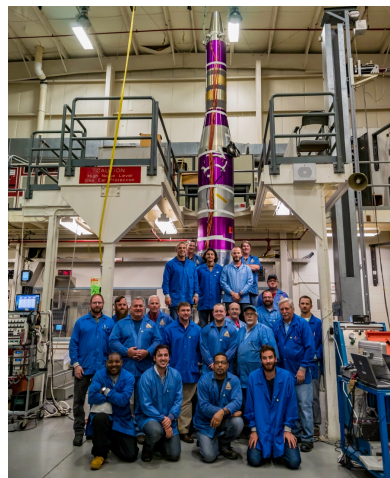
- Changes to parachute packing & rigging after SR02:
 - Deployment bag: reduce mass & re-design attachments to vent
 - Packing procedure: S-fold to slow down inflation & ensure more even mass distribution.
 - Triple bridle: Use Nylon structural elements (previously Kevlar) to reduce snatch loads
- Damage to parachute on SR03 was almost imperceptible



Conclusions



- ASPIRE's tests of a strengthened DGB were extremely successful
 - Highest loads ever survived in an supersonic parachute inflation
 - Parachute is considered ready for use on Mars2020
- Ongoing work:
 - 3D canopy shape reconstruction from stereo videography
 - Static aerodynamic coefficients & parachute/payload dynamics
- See also:
 - Nelessen *et al* "Mars 2020 Entry, Descent, and Landing System Overview"
 - Way *et al* "EDL Simulation Results for the Mars 2020 Landing Site Safety Assessment"
 - Webb *et al* "Systems Engineering for ASPIRE: A Low-Cost, High Risk Parachute Test Project"





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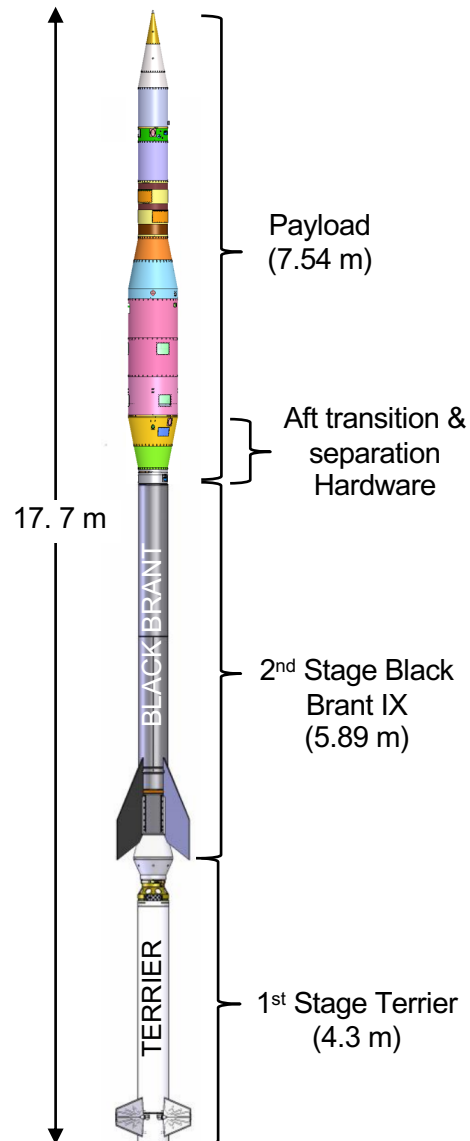
Backup



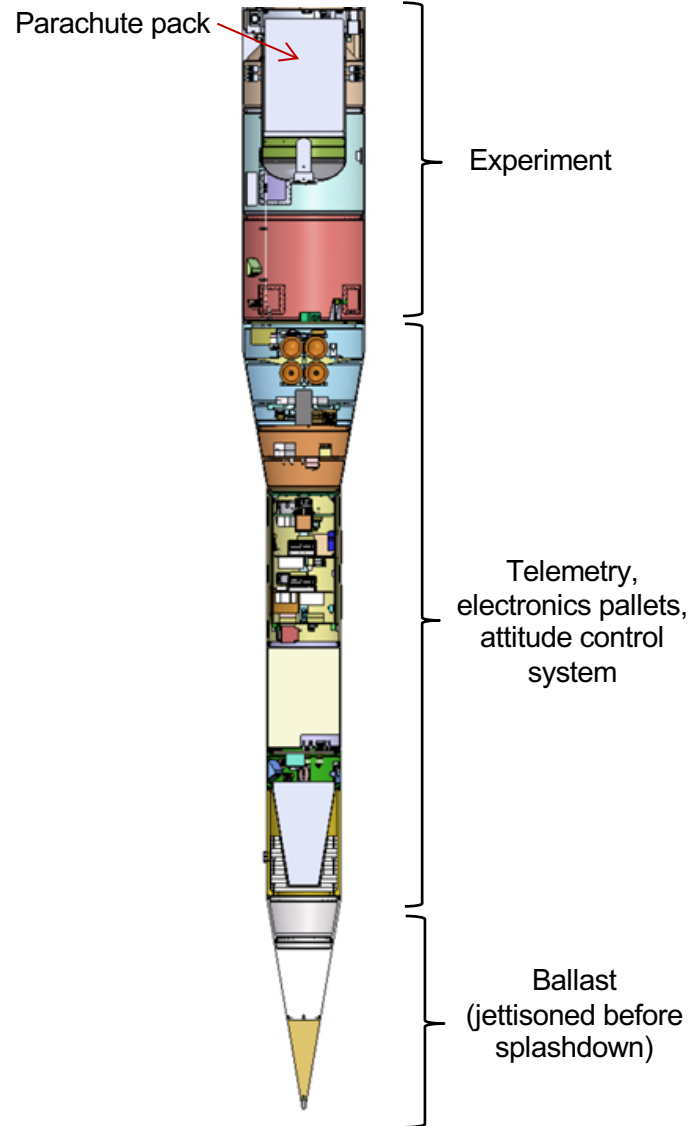
Test Architecture



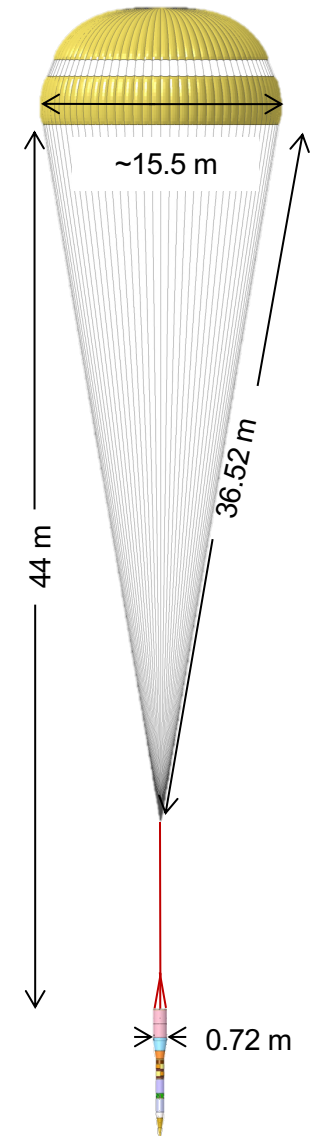
Launch Configuration



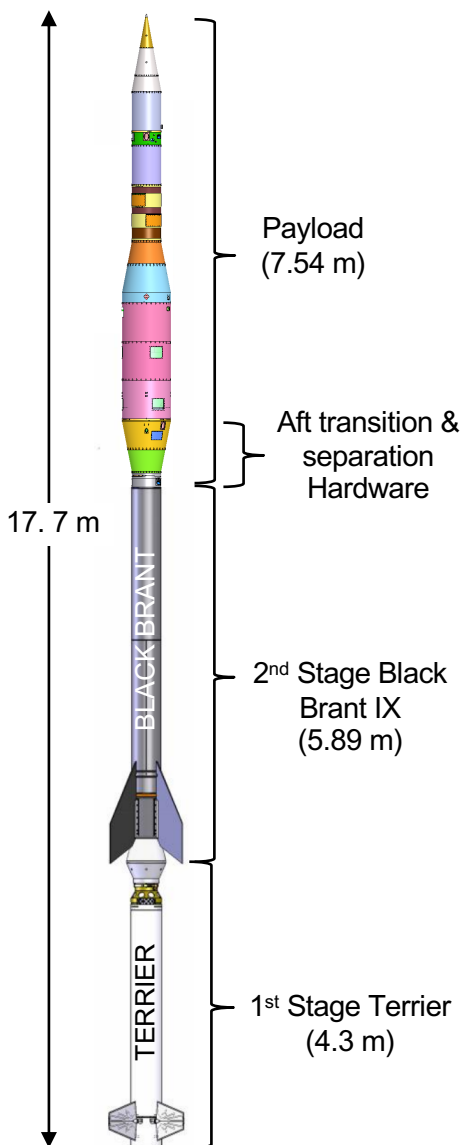
Start of Experiment Phase



Parachute Deployed Configuration



Test Architecture



- Rail-launched Terrier Black Brant
- Spin-stabilized at 4 Hz
- Yo-yo de-spin after 2nd stage burnout
- Mortar-deployed full-scale DGB
- Cold gas ACS active from payload separation to before mortar fire
- Recovery aids:
 - Foam provides buoyancy
 - Nosecone ballast (for additional mass & aerodynamic stability) is jettisoned before splashdown
- Payload mass:
 - Launch: 1268 kg
 - Post-separation: 1157 kg
 - Splashdown: 495 kg

